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ENVIRONMENTAL RESEARCH

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OPTSTOR USER'S MANUAL

R. A. C. PROJECT NO. 266 RR

Environment
Ontario
Jim Bradley, Minister

OPTSTOR USER'S MANUAL

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Prepared For
Ontario Ministry of the Environment

MAY 1988

By
MacLaren Plansearch Inc.
Toronto, Ontario

ISBN 0-7729-4677-9

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Prepared for:
Ontario Ministry of the Environment

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MacLaren Plansearch Inc.
May, 1988

c Queen's Printer for Ontario, 1988

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CONTENTS

PAGE

1 INTRODUCTION 1

1.1 What Is OPTSTOR? 3
1.2 Uses 4
1.3 Relationship to SWMM/EXTRAN 4
1.4 General Input Information 5
1.5 Methodology 6

2 INSTALLATION AND EXECUTION 10

2.1 Contents of OPTSTOR Diskette 10
2.2 Computer Hardware/Software Requirements 11
2.3 Computer Installation 11
2.4 How to Run OPTSTOR 12

3 INPUT DATA 13

3.1 Title 13
3.2 System 13
3.3 Pipes 14
3.4 Nodes 15
3.5 Storage Cost 15
3.6 Example 16

4 OUTPUT 17

4.1 Standard Output (Output Level 0) 17
4.2 Error Messages 18
4.3 Optional Calculation Details (Output Level 1,2,3, or N) 19

5 DEMONSTRATION SYSTEM 20

5.1 System Description 20
5.2 EXTRAN Simulation of Demonstration System 21
5.3 OPTSTOR Analysis of Demonstration System 21
5.4 EXTRAN Simulation of OPTSTOR Solutions 23

APPENDIX A RELATIONSHIP BETWEEN OPTSTOR AND DYNAMIC MODELS 25

A.1 GENERAL DESIGN METHOD 25
A.2 USING OPTSTOR IN CONJUNCTION WITH SWMM/EXTRAN 26
  A.2.1 The SWMM/EXTRAN Model 26
  A.2.2 Preparation for OPTSTOR Analysis 27
  A.2.3 OPTSTOR Analysis 28
  A.2.4 Simulation of Relief Measures Using SWMM/EXTRAN 29

CONTENTS (Continued)

PAGE

APPENDIX B DEVELOPMENT OF STORAGE/IMPERVIOUS AREA VERSUS FLOW REDUCTION CURVES 32

B.1 OVERVIEW 32
B.2 RESULTS 33

APPENDIX C COMPLEX METHOD FOR NONLINEAR CONSTRAINED OPTIMIZATION 35

C.1 OVERVIEW 35
C.2 OPTSTOR APPLICATION 35
C.3 DEVELOPING THE INITIAL SOLUTION COMPLEX 36
C.4 COMPLEX OPTIMIZATION 37

LIST OF FIGURES AND TABLES

Figure No.	Description	After Page
1	Flow Continuity	7
5.1	Plan View of Demonstration System	20
5.2	OPTSTOR Demonstration System Profile	20
A-1	Example of Network Decomposition	27
B-1 a)	In-line Storage: Assumed Shape of Outflow Hydrograph	32
B-1 b)	Off-line Storage: Assumed shape of Outflow Hydrograph	32
B-2	Approximate Storage Volume per Impervious Acre to Achieve Specified Percentage Reduction in 5 Year Peak Flow	33

Table No.	Description	After Page
5.1	CHARACTERISTICS OF DEMONSTRATION SYSTEM	20
5.2	SUMMARY STATISTICS FOR SWMM/EXTRAN SIMULATION OF UNMODIFIED DEMONSTRATION SYSTEM	21
5.3 a)	EXAMPLE OPTSTOR DATA SET: TRUNK IN-LINE	21
5.3 b)	EXAMPLE OPTSTOR DATA SET: LOCAL OFF-LINE	21
5.4 a)	OPTSTOR TRUNK IN-LINE RESULTS (ALL PIPES)	21
5.4 b)	OPTSTOR TRUNK IN-LINE RESULTS (2 PIPES)	21
5.5 a)	OPTSTOR LOCAL OFF-LINE RESULTS (ALL PIPES)	22
5.5 b)	OPTSTOR LOCAL OFF-LINE RESULTS (4 PIPES)	22

LIST OF FIGURES AND TABLES

(Continued)

Table No.	Description	After Page
5.6	SUMMARY OF EXTRAN SIMULATION OF TRUNK IN-LINE STORAGE	23
5.7	SUMMARY OF EXTRAN SIMULATION OF LOCAL OFF-LINE STORAGE	23

1 INTRODUCTION

Overloading of storm and combined sewers, during storm events, is common in many older systems in municipalities in Canada and elsewhere. On a national scale, problems related to overloading have been reported in Calgary, Edmonton, Kingston, Ottawa, Saskatoon, Toronto, Windsor, and Winnipeg. In Metropolitan Toronto alone, examples can be found in the cities of Etobicoke, North York, Scarborough, Toronto, and York.

A variety of practices are to blame for these problems. Typically, new areas of development have been connected to existing systems not designed to handle the increased inflows. However, in some cases, redevelopment of downtown areas has increased imperviousness and consequently surface runoff contributing to sewer inflows. In other cases, older systems were sized to a lower design standard than is common today (e.g., a 2-year design rainfall as opposed to a 10-year rainfall). Inevitably, such practices lead to surcharging, and potential overloading, of existing sewers systems.

Some examples of the problems associated with overloading include basement flooding, street flooding, combined sewer overflows and overloading of treatment plants leading to bypasses. All of these problems result in pressure on the municipality, from the public and regulatory agencies, to upgrade inadequate systems.

Traditionally, such sewer relief schemes have concentrated on increasing the capacity of the system. Methods which have been used include:

- replacing existing pipes with larger ones
- twinning existing pipes
- diverting flows from one system to another with spare capacity

- creating new outfalls from the system
- separating combined sewers into storm and sanitary systems

These methods are generally successful in solving the problems of surcharging but can be very expensive to implement. In addition, they can result in undesirable side effects such as water pollution from increased discharges of untreated flow to receiving streams.

In recent years there has been considerable interest in alternative methods of dealing with sewer relief. Storm water storage is one of these methods. The most obvious use of this concept has been in the related area of stormwater management for new developments. However, the approach has also proved cost-effective in relieving surcharging in existing systems in the cities of Saskatoon, Scarborough and York.

Implementations of storage can be grouped into two types: end-of-pipe and in-system. The former is useful in reducing overflows to a receiving water body but not in surcharge relief. Consequently, it is not considered further in this manual. In-system storage is distributed at critical points within the system.

In-system storage can be classified into two types, referred to in this manual as 'local' and 'trunk' storage. These can be implemented as either 'in-line' or 'off-line' storages. These four storage methods can be described as follows:

Trunk In-line Storage - This type of storage is often referred to as a 'superpipe'. It is located on the sewer line with all upstream flow passing through it. In general, it would consist of a larger pipe or vault with a restricted outlet.

Trunk Off-line Storage - This type of storage consists of a diversion of flow above a design threshold from a main sewer line into a holding tank or pond with a controlled release, back to the main sewer line, after the peak flow has occurred.

Local In-line Storage - This type of storage is designed to temporarily store local inflows to the trunk system. One example is the capture of road and rooftop flows in a surface pond prior to release into the sewer system.

Local Off-line Storage - This type of storage is also designed to capture local inflows before they reach the trunk sewer system. However, this would be implemented as a diversion of flow above a design threshold.

In a large and/or complex sewer system with many pipes, inflow points, diversion points, etc., it is very difficult to determine intuitively where the best locations for such storage are. To determine exactly what volume(s) would be cost-effective is even more difficult. One approach is to make educated guesses and to simulate the system with proposed storages in place, using a dynamic sewer routing model such as EXTRAN. The main disadvantage of this trial-and-error method is that it may require many simulations, taking many days of work by a skilled modeller. In addition, with computer costs of up to several hundred dollars per run for complex systems, these expenses alone can be prohibitive.

A powerful tool is needed by the modeller to reduce the required simulations to a minimum by providing a good estimate of the location and size of the required storages. This is the purpose of OPTSTOR.

1.1 What Is OPTSTOR?

OPTSTOR is an engineering design tool. It is intended to help in selecting the most cost-effective method of relieving an overloaded sewer system. OPTSTOR is a computer program which estimates OPTimum STORage volumes and locations to reduce sewer system flows to acceptable levels. However, OPTSTOR alone is incomplete. It requires a broader design methodology in that OPTSTOR must be used in conjunction with an urban runoff/dynamic flow routing model such as the RUNOFF and EXTRAN Blocks of SWMM as part of an overall analysis and design process.

At its core, OPTSTOR is a method of searching for the optimum solution to a constrained optimization problem. The hydraulic characteristics of the sewer line under investigation form the constraints. For example, there is a maximum safe head at each manhole in the system. The objective of the search is to minimize the cost of meeting the constraints. This is achieved by finding the 'best' locations and volumes of storage to reduce flows in the system to an acceptable level. In some cases, however, the 'best' solution is a combination of storage and more traditional methods such as pipe enlargements. OPTSTOR allows the user to examine combinations of storage and pipe replacement. The methods used by OPTSTOR are described in Section 1.5.

1.2 Uses

The main uses of OPTSTOR are:

i) to determine cost-effective locations and sizes of both 'local' and/or 'trunk' storage to provide relief in an overloaded sewer system

ii) to examine combinations of sewer enlargement and storage to provide relief

OPTSTOR is most effective for a large and/or complex system. While it may be useful for a simple system, it has the greatest advantage where the solution is not intuitively obvious. Many complex simulations with EXTRAN, or some similar model, can be reduced by using OPTSTOR as a guide to the sizing and placement of relief storage.

1.3 Relationship to SWMM/EXTRAN

As previously noted, OPTSTOR is used as part of an overall design method in combination with an urban runoff model and a dynamic flow routing model of the sewer system. To date, it has been used with only the SWMM/EXTRAN model. It could, however, be used in combination with other systems such as the Dorsch model.

The general approach is as follows:

i) A SWMM/RUNOFF and EXTRAN model of the subject system is established and the design flows for the existing situation are simulated.

ii) The system is conceptually decomposed into a set of individual sewer lines which will be modelled separately using OPTSTOR.

iii) The first line to be considered is selected and peak inflows at each node (manhole) in this sewer line are abstracted from the SWMM RUNOFF model. The downstream water level is obtained from EXTRAN.

iv) The OPTSTOR input is prepared and with the input from the SWMM/EXTRAN simulations included, a series of OPTSTOR runs are carried out until a solution for this line is obtained.

v) The other lines are examined using OPTSTOR.

vi) The EXTRAN model input is modified to account for the proposed storages and pipe enlargements and a simulation is carried out for the design inflows.

vii) If necessary, steps iii) to vi) are repeated to refine the solution.

The relationship between SWMM/EXTRAN and OPTSTOR is further detailed in Appendix A.

1.4 General Input Information

The program requires one ASCII input data file, which is created and modified by means of an editor or word processing package. After OPTSTOR is run, a single output file is created. As described in Section 2.4, the program prompts for the names of the input and output files, after the command to run OPTSTOR is given. The user must ensure that extraneous control characters are not inadvertently inserted when the input file is created and modified.

Each 80-column record in the ASCII input file, prepared prior to running OPTSTOR, consists of a four-letter code (in the first four columns), followed by one or more fields. The code and fields are delimited by one or more blank spaces. Though the fields must be provided in the order specified in Section 3, they are entered in free format. In free format, there is no need to distinguish between integer (whole) numbers and real (decimal) numbers. Thus to input the integer sixteen, "16", "16.0", etc. are equally acceptable.

OPTSTOR checks certain input data and issues an error message (see Section - 4.1) if a problem is detected. Depending on the severity of the error, the program will either continue processing after internally assigning a default value or it will stop. Any input field with a limited number of possible values is checked : four-letter code, location of storage, type of storage, level of output and availability of storage. In addition, fields which are bounded are also screened : integer labels (for pipes and nodes), Manning's roughness coefficient and superpipe ratio.

The consistency and reasonableness of the physical aspects of the system (e.g., pipe diameter, pipe slope, impervious area and nodal inflows) are not checked.

Both pipes and nodes must be entered from upstream to downstream.

1.5 Methodology

There are two major components in OPTSTOR:

- development of initial feasible solutions

- improvement of the initial solutions

The program treats the ratios R of the stored flow to the storable flow at the nodes as the independent variables. Due to economic considerations, the maximum value of R is limited to 0.9. Once all the ratios are given, the program calculates flows, heads, storage volumes and costs. The heads must not exceed maximum allowable values.

At the outset, the existence of a solution is determined by allocating maximum storage (R=0.9) at each node where storage is permitted. If a solution exists and nonzero storage is needed, then initial feasible solutions are randomly developed in order to span the solution space reasonably well.

The Complex Method, due to Box (1965), is used to generate improved feasible solutions (see Appendix C). In essence, the procedure entails the replacement of the worst solution in each iteration by its reflection about the centroid of the other solutions. The method also provides for the case wherein the reflection is still the worst solution or is infeasible (i.e., violates one or more constraints).

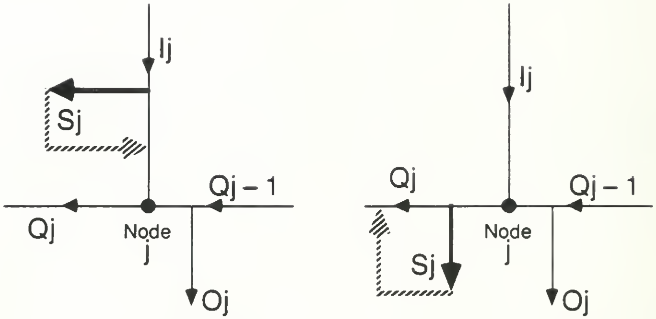
The flows in the pipe series are modelled in steady state. OPTSTOR ensures that the following are satisfied:

- flow continuity at each node
- head loss in each pipe

Continuity

As shown in Figure 1, there are five flow components at each node j:

- upstream flow, $Q(j-1)$
- local inflow, $I(j)$
- flow diversion (outflow), $O(j)$
- stored flow, $S(j)$
- downstream flow, $Q(j)$



(a) Local Storage (b) Trunk Storage

Legend

I – Inflow
O – Diversion Flow (±)
Q – Trunk flow
S – Stored flow

Figure 1
Flow Continuity

In steady state, continuity requires that

$$Q(j) = Q(j-1) + I(j) - O(j) - S(j)$$

The storable flow is based on the location of storage as shown in the following table.

Location	Storable Flow
local	inflow (= I(j))
trunk	total flow (= Q(j-1) + I(j) -O(j))

In either event, the ratio R (stored flow/storable flow) cannot exceed 0.9.

Head Loss

By means of the same loss equation used in the EXTRAN model (viz., Manning's Formula), the change in head is calculated from node to node. It is assumed that the circular pipes are full or surcharged. Hence, if the conservative assumption is made that the hydraulic grade line and the energy grade line are coincident, then (in Imperial units) the head loss H in a pipe is calculated as follows:

$$H = 4.665 \ (n\ Q)^2\ L\ /\ D^{5.33} \qquad \text{(ft)}$$

where n is the Manning's roughness coefficient, Q is the pipe flow, D is the diameter and L is the length. Should the flow in any pipe not be full, then OPTSTOR sets the head equal to the obvert. Local losses can be combined with pipe losses by increasing n appropriately.

For noncircular pipes, the user is cautioned against selecting "equivalent" circular pipes to represent his system. The problem relates to the need for three inconsistent equivalencies: area, wetted perimeter and obvert. Thus, OPTSTOR should be restricted to circular pipes.

In a superpipe, there is little head loss. Thus, in any pipe whose upstream end is a superpipe, the head loss is calculated on the basis of the input data for the downstream section while the upstream part usually has a minimal loss based on the size of the superpipe.

2 INSTALLATION AND EXECUTION

This section of the manual describes the computer hardware requirements, the installation procedure, and the operation of the OPTSTOR model.

2.1 Contents of OPTSTOR Diskette

The OPTSTOR model is distributed on a single 5.25-inch, 360-kilobyte, double-sided, double-density floppy diskette. The following files are contained on the disk.

File Name	Description
OPTSTOR.FOR	- the FORTRAN code for OPTSTOR
OPTSTOR.CMN	- the common variables ($INCLUDE:)
OPTSTOR.EXE	- the executable version of OPTSTOR
HELP.BAT	- batch file to display help files

A second floppy diskette contains sample input and output files from the demonstration system (cf.,Section 5).

File Name	Description
DL04.DAT	- local off-line sample input
DL04.OUT	- local off-line sample output
DTI2.DAT	- trunk in-line sample input
DTI2.OUT	- trunk in-line sample output
DEMO.SWM	- SWMM Version 3, original input
DL04.SWM	- SWMM Version 3, local off-line input
DTI2.SWM	- SWMM Version 3, trunk in-line input

2.2 Computer Hardware/Software Requirements

The OPTSTOR model requires the following hardware and software configuration.

- IBM PC/XT/AT or compatible microcomputer
- 512 kilobytes of RAM
- two 5.25-inch floppy disk drives or one floppy disk drive and a hard disk (desirable though a single floppy disk drive may be adequate)
- an 8087 or 80287 math co-processor
- PC-DOS or MS-DOS Version 2.1 or higher
- a display adaptor which can display 80 columns of text on a line
- an 80-column printer is necessary for producing hard copy of standard output files (132 columns needed for output levels 1, 2, ...)

2.3 Computer Installation

The first thing you should do is to make a working copy of your OPTSTOR diskette using the DOS COPY A:*.* B: command. Store the original disk in a safe place and use the copy in your day-to-day work.

If your computer has a hard disk, you may want to copy the contents of the OPTSTOR disk into a subdirectory of the hard disk. This will enable you to run OPTSTOR without the need for floppy diskettes. Consult your DOS manual for the correct commands for using subdirectories.

If you are using a floppy disk system, you only need a working copy of the OPTSTOR diskette to run the model.

2.4 How to Run OPTSTOR

To run OPTSTOR on a floppy-based system, place the OPTSTOR working disk in drive B and the data disk in drive A. Set the default drive to A and enter the command

```
B:OPTSTOR
```

You will be then prompted for the names of the input file, which should be on the default or A disk, and the output file which will be written to the default disk.

The procedure is similar for a hard-disk system, but both the program and data can be kept in the same subdirectory. In this case you enter the command

```
OPTSTOR
```

without the drive specifier in front of it.

If you try to use an input file that does not exist, you will be asked to enter a new input file name. If the output file you specify already exists, you will be given the option of changing the name of the output file, or writing over the existing file, or stopping the program.

To verify your copy of OPTSTOR, you can run the two sample data files included on the second distribution disk. The correct output for the sample problems is also on the disk. Each problem will take about 1 minute to execute on a micro equipped as specified in Section 2.2 with a math co-processor.

The Microsoft FORTRAN Compiler, Version 4.0, was used to create the executable version of OPTSTOR.

3 INPUT DATA

OPTSTOR requires one input data file. This file must be created, prior to running OPTSTOR, using any editor or word-processing package which can produce a standard ASCII file. If one uses a word processing package, the file should be created in non-document mode.

Each input data record starts with a four-letter code. This code must appear in the first four columns of each record and be followed by a minimum of one blank space. The second and succeeding records with the same code can alternatively start with merely a "D" (for "ditto") in column one, followed by at least four blank spaces. This alternate code is acceptable for pipe and node records, as long as the preceding record has the same code.

Input data are entered in free format. It is necessary to provide all required input data in the correct order as listed below, separated by one or more blanks. The program does not verify the presence of each required input; only specific control inputs (marked with an * below) are checked.

3.1 Title

Position		Required Input Data
1	*	title code "TITL"
2		title for the run (maximum 75 characters)

3.2 System

Position		Required Input Data
1	*	record code "SYST"
2		number of pipes in the series
3		most downstream head for the pipe series (ft)

4	*	location of storage 0 = local 1 = trunk
5	*	type of storage 0 = off-line 1 = in-line
6	*	level of output 0 = standard (input and final results) 1 = calculation details included for every iteration 2 = calculation details included for every 10th iteration 3 = calculation details included for every 100th iteration n = calculation details included for every iteration starting at the nth one (n >10)

3.3 Pipes

Repeat record for each circular pipe in the series starting with the upstream pipe and proceeding sequentially downstream.

Position		Required Input Data
1	*	record code "PIPE"
2		integer label (maximum of 4 digits)
3		diameter (ft)
4		length (ft)
5		Manning's roughness coefficient (eg., 0.015)
6		upstream invert (ft)
7		downstream invert (ft)
8	*	superpipe ratio. If part of the pipe (viz., upstream end) is a superpipe, this is the ratio of the length of the superpipe to that of the original pipe (i.e., between 0.0 and 1.00).

3.4 Nodes

Repeat record for each node in the series starting with the upstream node and proceeding sequentially downstream, excluding the most downstream node.

Position		Required Input Data
1	*	record code "NODE"
2		integer label (maximum of 4 digits)
3		impervious area contributing to inflow (acres)
4	*	local inflow (cfs)
5	*	trunk flow diversion into (positive) or out of (negative) the sewer line (cfs)
6	*	storage availability 0 = no storage available 1 = storage available
7		maximum allowable head (ft)

3.5 Storage Cost

Storage cost ($) is expressed as a linear function of volume, V (cfs), with an optional second rate:

$$a + b\ V$$

Position		Required Input Data
1	*	record code "COST"
2		constant coefficient, a ($)
3		linear coefficient, b_1($/cu.ft)
4		volume above which second rate becomes effective (cu.ft.)
5		second rate, b_2($/cu.ft)

3.6 Example

The following example input file is from the demonstration system.

```
TITLE    DEMONSTRATION   SYSTEM:   LOCAL OFF-LINE    (ALL PIPES)
SYST        11  560.00      0         0        0
PIPE       801    4.50    571.00      0.013  640.73    637.96    0.50
D          803    5.50   2941.00      0.013  637.47    620.62    0.10
D          805    5.50    459.00      0.013  620.12    616.81    0.50
D           11    6.00    393.00      0.013  614.79    611.89    0.50
D            9    6.00    556.00      0.013  611.61    607.63    0.50
D            8    6.00    500.00      0.013  607.03    603.96    0.50
D            7    6.00    598.00      0.013  603.53    597.05    0.50
D            6    6.00    393.00      0.013  584.86    580.38    0.50
D            5    6.00    545.00      0.013  569.75    563.55    0.50
D            4    6.90    508.00      0.013  562.55    559.73    0.50
D            3    6.90    892.00      0.013  559.65    553.87    0.25
NODE       801   43.81    140.38       0.00     1    647.73
D          803   30.04     89.22       0.00     1    644.47
D          805   26.95     74.21       0.00     1    628.15
D           11   23.35     72.33     136.00     1    631.57
D            9    0.00      0.00      22.60     1    629.9
D            8    0.00      0.00      20.00     1    627.3
D            7    7.00     25.45       0.00     1    619.98
D            6    7.14     25.65       0.00     1    603.2
D            5    2.03      7.59       0.00     1    586.5
D            4   14.28     45.59       0.00     1    571.23
D            3    5.77     24.72       0.00     1    568.63
COST       0.0   10.00      0.00      10.00
```

4 OUTPUT

This section of the manual describes the standard output, error messages, and the (optional) supplementary information produced by the OPTSTOR program.

4.1 Standard Output (Output Level 0)

The standard output is divided into three sections.

The first section is a literal echo of the user's input file. This is provided to facilitate the correction of input data as prompted by the output error messages.

The second section of the standard output is a complete summary of the input data in tabular form for the pipe series being modelled. This section includes the System Specification, Pipe Data, Node Data, and Storage Cost Data. It is advisable to check the order and correspondence of all data to ensure that the correct information has been provided and that data describe the appropriate pipe or node. (The OPTSTOR program only checks the values of particular control variables and not the appropriateness of the user's description of pipes and nodes.)

The final section of the standard output presents the results of the OPTSTOR modelling of the pipe series. These include the following:

i) flow rate, velocity, and head loss in each pipe

ii) head, reduction in flow, storage volume, and storage cost at each node

iii) storage volume and storage cost for the entire system

4.2 Error Messages

Two types of error messages can be signalled to the user by the OPTSTOR program: Warnings and Stops.

Warning messages do not cause program termination directly. They signal that an input field may be erroneous and indicate whether a default value is substituted. In addition, they are intended to alert the user that particular actions, inherent in the Complex Method, have led to unfavourable results during an intermediate step so that a deviation from the standard procedure has been implemented to avoid errors that would result from following the standard procedure. The two results that trigger a warning are as follows (cf., Appendix C):

i) The centroid of the complex solutions represents a non-solution (i.e., constraints violated).

ii) The solution represented by the centroid of the complex solutions has a greater cost, for the total storage required, than all of the solutions in the complex.

Stop messages result from serious errors in input data or in program execution. As the name implies, these cause immediate program termination. The most likely reason for a Stop message to occur is as a result of input records being entered in an incorrect format or order. The resulting message will alert the user to the offending record.

A Stop message can also be generated as a cumulative result of Warning messages. It is possible, under certain circumstances, that deviations (from the standard Complex procedure) implemented to avoid errors during intermediate steps will not achieve their desired result and so program termination will occur. The accompanying message will indicate the nature of the fatal error encountered and a summary of the results for the current minimum will be included.

4.3 Optional Calculation Details (Output Level 1,2,3, or N)

Intermediate details of program calculations are available by setting the last (sixth) input of the "SYST" record equal to 1, 2, 3, or n (>10). The user is warned that, if these optional details are selected, the quantity of output can be very large and its creation very time-consuming.

Output, for these output levels, are divided according to the structure of the program. The first part of the output describes the initial solutions created to form the solution complex. The solutions are described in terms of two variables; the independent variable at each location (i.e., the ratio of stored flow to the total storable flow at a node) and the cost of the total storage required by the solution.

Subsequent output describes the results of the steps the program follows in search of a lower cost solution. This output includes, for selected iterations of the Complex Method, the value of the independent variable that describes each newly developed solution at each node, the cost of the total storage required for each solution "point" of the complex and the centroid of the complex without its "worst" point.

The Standard Output (cf., Section 4.1) is also provided.

5 DEMONSTRATION SYSTEM

This section describes the application of OPTSTOR to a selected demonstration system. The system selected is a relatively simple one chosen in the interests of a clear illustration of the characteristics of OPTSTOR. In general, OPTSTOR would be applied to more complex systems for which an intuitive approach to selecting storage locations and volumes would be less likely to be successful. The system illustrated can be thought of as one line isolated from a more complex network (cf., Appendix A).

5.1 System Description

The demonstration system is a trunk sewer located in the Town of Vaughan just north of Metropolitan Toronto. Since it was designed within the past few years, it is not in fact overloaded and not in need of relief. To create an overloaded condition, a hypothetical area was appended to the system near its upper end. The inflow from this hypothetical area is conveyed through an additional pipe and is modelled as a trunk inflow.

The resulting demonstration system is shown in plan in Figure 5.1. The main sewer line is shown in profile in Figure 5.2. The system, moving downstream, consists of fifteen pipes numbered 801, 803 to 805, 12, 11, and 9 to 1. These pipes connect sixteen nodes which are numbered such that the upstream node corresponds to the number of the pipe downstream of it. The outlet node is numbered 100. Of the sixteen nodes, only eleven have inflows from the surrounding catchment areas. These inflows were input to EXTRAN as "card hydrographs". Pipe 12 is treated as a positive diversion contributing trunk flow at node 11. Dry weather trunk flows occur at two nodes: 9 and 8. Salient characteristics of the system are listed in Table 5.1. The Manning's friction coefficient n is 0.013 for all pipes.

Pipe offsets between nodes 7 to 5 are represented in EXTRAN by means of introducing nodes 601 to 501 and subdividing the pipes accordingly. In OPTSTOR, nodes 601 and 501 do not appear.

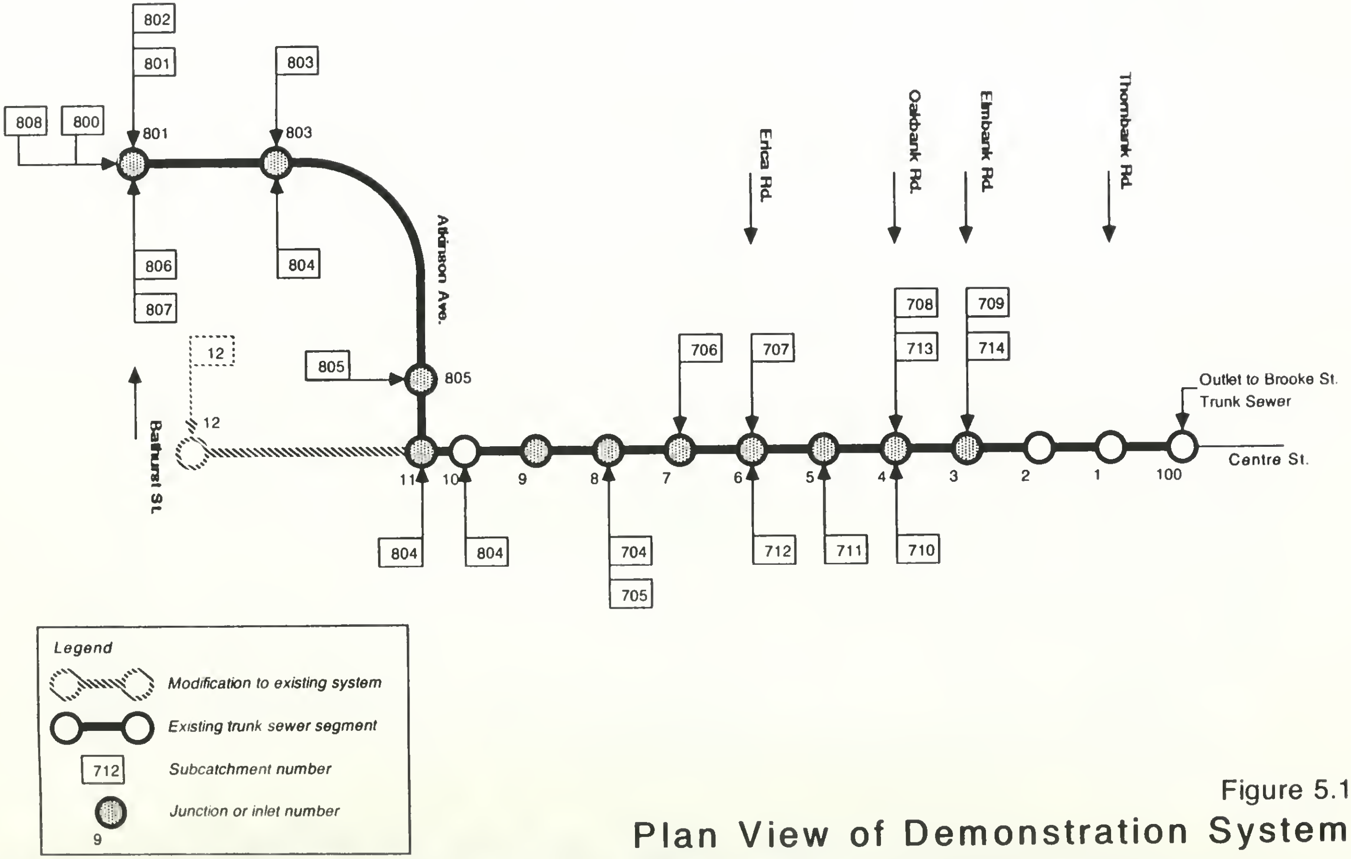


Figure 5.1

Plan View of Demonstration System

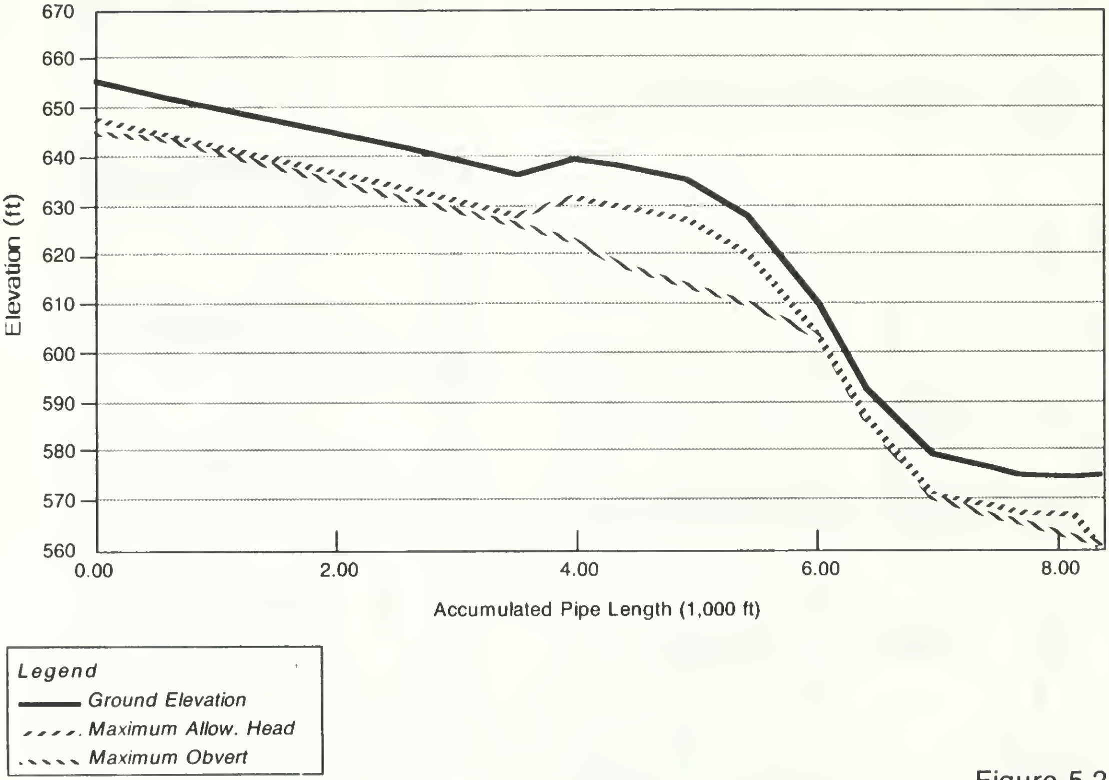


Figure 5.2
OPTSTOR Demonstration System Profile

TABLE 5.1 CHARACTERISTICS OF DEMONSTRATION SYSTEM

a) Characteristics of Pipes

Pipe No.	Label	U/S Node	D/S Node	Pipe Diameter (ft)	Pipe Length (ft)	D/S Offset (ft)
1	801	801	803	4.5	571	0.49
2	803	803	804	5.5	2024	0.00
2	804	804	805	5.5	917	0.50
3	805	805	11	5.5	459	2.02
-	12	12	11	4.5	300	0.00
4	11	11	9	6.0	393	0.28
5	9	9	8	6.0	556	0.60
6	8	8	7	6.0	500	0.43
7	7	7	601	6.0	598	0.00
-	601	601	6	6.0	200	0.00
8	6	6	501	6.0	393	0.00
-	501	501	5	6.0	200	0.00
9	5	5	4	6.0	545	1.00
10	4	4	3	6.9	508	0.08
11	3	3	2	6.9	218	0.00
11	2	2	1	6.9	458	0.15
11	1	1	100	6.9	216	0.00

b) Characteristics of Nodes

Node No.	Label	Imp. Area (acres)	Inflow (cfs)	Diversion (cfs)	Max. Allowable Head (ft)
1	801	43.8	140.38	0.00	647.73
2	803	30.0	89.22	0.00	644.47
3	805	26.9	74.21	0.00	628.15
4	11	23.3	72.33	136.00	631.57
5	9	0.00	0.00	22.60	629.90
6	8	0.00	0.00	20.00	627.30
7	7	7.0	25.45	0.00	619.98
8	6	7.1	25.65	0.00	603.20
9	5	2.0	7.59	0.00	586.50
10	4	14.3	45.59	0.00	571.23
11	3	5.8	24.72	0.00	568.63

5.2 EXTRAN Simulation of Demonstration System

The first step of the analysis of the demonstration system is to perform a EXTRAN simulation for the existing condition. A 5-year return period design storm (4-hour Chicago) is utilized. Table 5.2 shows the peak flows in the pipes and hydraulic grade line in the system. As indicated, the system is surcharged to the ground level at several nodes.

5.3 OPTSTOR Analysis of Demonstration System

The OPTSTOR data sets for the demonstration system are shown in Tables 5.3 a) and b). They are assembled according to the instructions contained in Section 3 and procedures described in Appendix A. The main difference from the EXTRAN data is that the nodes at which there are no local inflow have not been included. Between these nodes, the pipes have been lumped together as a single equivalent pipe. Thus, pipes 803 and 804 are combined as pipe 803; similarly, pipes 1, 2 and 3 are lumped as pipe 1. At nodes 6 and 5, pipe offsets in excess of what EXTRAN's methodology can accommodate are replaced by "dummy conduits".

Solutions, for the demonstration system, are developed using both local off-line storage and trunk in-line storage. The following describes the results of the OPTSTOR analysis:

i) Trunk In-line Storage: Table 5.4 a) shows the system flows, maximum water levels, calculated storages and cost for the OPTSTOR trunk in-line solution if all nodes are eligible for storage. Storage is concentrated at four nodes: 801, 9, 4 and 3. Because trunk in-line storage is least expensive upstream in a sewer line where the trunk flow hydrograph is less broad (cf., Appendix B), storage is subsequently limited to nodes 801 and 9. The results of this storage configuration appear in Table 5.4 b).

TABLE 5.2 SUMMARY STATISTICS FOR SWMM/EXTRAN SIMULATION OF UNMODIFIED DEMONSTRATION SYSTEM

Conduit/ Junction No.	Ground Elevation (ft)	Maximum Allowable Head (ft)	Maximum Head (ft)	Maximum Flow (cfs)
801	655.70	647.7	655.70	143.1
803	652.50	644.5	652.50	226.3
804	641.70	633.7	641.70	224.0
805	636.20	628.2	636.20	268.4
12	640.00	632.0	640.00	136.0
11	639.60	631.6	639.60	424.2
9	637.90	629.9	637.90	446.8
8	635.30	627.3	635.30	466.9
7	628.00	620.0	628.00	489.4
601	609.00	603.2	600.56	507.3
6	609.90	603.2	609.90	519.0
501	592.80	586.5	583.54	523.9
5	592.80	586.5	592.12	535.6
4	579.20	571.2	577.33	585.3
3	576.60	568.6	571.87	609.8
2	575.30	567.3	568.84	607.1
1	574.90	566.9	564.11	611.1
100	575.30	567.3	560.17	

TABLE 5.3 a) EXAMPLE OPTSTOR DATA SET:
TRUNK IN-LINE

```
TITLE   DEMONSTRATION SYSTEM: TRUNK IN-LINE    (ALL PIPES)

SYST        11    560.00          1         1         0
PIPE       801      4.50     571.00     0.013    640.73  637.96   0.50
D          803      5.50    2941.00     0.013    637.47  620.62   0.10
D          805      5.50     459.00     0.013    620.12  616.81   0.50
D           11      6.00     393.00     0.013    614.79  611.89   0.50
D            9      6.00     556.00     0.013    611.61  607.63   0.50
D            8      6.00     500.00     0.013    607.03  603.96   0.50
D            7      6.00     598.00     0.013    603.53  597.05   0.50
D            6      6.00     393.00     0.013    584.86  580.38   0.50
D            5      6.00     545.00     0.013    569.75  563.55   0.50
D            4      6.90     508.00     0.013    562.55  559.73   0.50
D            3      6.90     892.00     0.013    559.65  553.87   0.25
NODE       801     43.81     140.38      0.00       1    647.73
D          803     30.04      89.22      0.00       1    644.47
D          805     26.95      74.21      0.00       1    628.15
D           11     23.95      72.33    136.00       1    631.57
D            9      0.00       0.00     22.60       1    629.9
D            8      0.00       0.00     20.00       1    627.3
D            7      7.00      25.45      0.00       1    619.98
D            6      7.14      25.45      0.00       1    603.2
D            5      2.03       7.59      0.00       1    586.5
D            4     14.28      45.59      0.00       1    571.23
D            3      5.77      24.72      0.00       1    568.63
COST         0.0   10.0        0.0      10.0
```

TABLE 5.3 b) EXAMPLE OPTSTOR DATA SET: LOCAL OFF-LINE

```
TITLE   DEMONSTRATION SYSTEM: LOCAL  OFF-LINE  (ALL PIPES)

SYST      11    560.00          0          0          0
PIPE     801      4.50     571.00      0.013     640.73   637.96    0.50
D        803      5.50    2941.00      0.013     637.47   620.62    0.10
D        805      5.50     459.00      0.013     620.12   616.81    0.50
D         11      6.00     393.00      0.013     614.79   611.89    0.50
D          9      6.00     556.00      0.013     611.61   607.63    0.50
D          8      6.00     500.00      0.013     607.03   603.96    0.50
D          7      6.00     598.00      0.013     603.53   597.05    0.50
D          6      6.00     393.00      0.013     584.86   580.38    0.50
D          5      6.00     545.00      0.013     569.75   563.55    0.50
D          4      6.90     508.00      0.013     562.55   559.73    0.50
D          3      6.90     892.00      0.013     559.65   553.87    0.25
NODE     801     43.81     140.38       0.00          1   647.73
D        803     30.04      89.22       0.00          1   644.47
D        805     26.95      74.21       0.00          1   628.15
D         11     23.35      72.33     136.00          1   631.57
D          9      0.00       0.00      22.60          1   629.9
D          8      0.00       0.00      20.00          1   627.3
D          7      7.00      25.45       0.00          1   619.98
D          6      7.14      25.65       0.00          1   603.2
D          5      2.03       7.59       0.00          1   586.5
D          4     14.28      45.59       0.00          1   571.23
D          3      5.77      24.72       0.00          1   568.63
COST        0.0   10.0        0.0       10.0
```

TABLE 5.4 a) OPTSTOR TRUNK IN-LINE RESULTS (ALL PIPES)

```
** PIPE RESULTS **

NUMBER    LABEL      FLOW      VELOCITY    HEAD LOSS
                     (CFS)      (FT/S)       (FT)

   1       801      132.61       8.34        2.26
   2       803      221.82       9.34       14.85
   3       805      295.98      12.46        2.67
   4        11      504.24      17.83        4.09
   5         9      522.84      18.49        4.35
   6         8      542.73      19.20        6.05
   7   [illegible]  568.04      20.09        7.91
   8         6      593.38      20.99       16.67
   9         5      600.62      21.24       15.15
  10         4      645.08      17.25        3.15
  11         3      668.13      17.87        8.08

** NODE RESULTS **

NUMBER    LABEL     HEAD      Q(IN/OUT)   REDUCTION   STORAGE     STORAGE
                                           IN FLOW    VOLUME       COST
                    (FT)        (CFS)      (CFS)     (CU. FT)      ($)

   1       801      645.2       0.00        7.77     26433.4     264334.
   2       803      643.0       0.00        0.01       609.4       6094.
   3       805      628.1       0.00        0.05      1627.5      16275.
   4        11      625.5     136.00        0.07      1809.6      18096.
   5         9      621.4      22.60        4.01     21886.8     218868.
   6         8      617.0      20.00        0.11      2280.7      22807.
   7         7      611.0       0.00        0.14      2743.6      27436.
   8         6      603.0       0.00        0.31      4618.6      46186.
   9         5      586.4       0.00        0.35      5006.1      50061.
  10         4      571.2       0.00        1.14     10992.2     109922.
  11         3      568.1       0.00        1.67     14160.9     141609.

** SYSTEM RESULTS **

TOTAL STORAGE VOLUME (1000 CU. FT.)          92.2
TOTAL COST FOR STORAGE ($1000s)             921.7
```

TABLE 5.4 b) OPTSTOR TRUNK IN-LINE RESULTS (2 PIPES)

```
** PIPE RESULTS **

NUMBER    LABEL      FLOW       VELOCITY     HEAD LOSS
                     (CFS)       (FT/S)       (FT)

   1       801        16.50        1.04         2.26
   2       803       105.72        4.45        16.85
   3       805       179.93        7.57         2.45
   4        11       388.26       13.73         3.30
   5         9       410.86       14.53         5.23
   6         8       430.86       15.24         5.17
   7         7       456.31       16.14         6.93
   8         6       481.96       17.05        16.67
   9         5       489.55       17.31        15.15
  10         4       535.14       14.31         3.84
  11         3       559.86       14.97         7.39

** NODE RESULTS **

NUMBER    LABEL     HEAD       Q(IN/OUT)      REDUCTION    STORAGE      STORAGE
                                               IN FLOW     VOLUME        COST
                    (FT)        (CFS)          (CFS)      (CU. FT)      ($)

   1       801      645.2        0.00         123.88     147170.2     1471702.
   2       803      643.0        0.00           0.00          0.0           0.
   3       805      626.1        0.00           0.00          0.0           0.
   4        11      623.7      136.00           0.00          0.0           0.
   5         9      620.4       22.60           0.00          0.0           0.
   6         8      615.2       20.00           0.00          0.0           0.
   7         7      610.0        0.00           0.00          0.0           0.
   8         6      603.0        0.00           0.00          0.0           0.
   9         5      586.4        0.00           0.00          0.0           0.
  10         4      571.2        0.00           0.00          0.0           0.
  11         3      567.4        0.00           0.00          0.0           0.

** SYSTEM RESULTS **

TOTAL STORAGE VOLUME (1000 CU. FT.)          147.2
TOTAL COST FOR STORAGE ($1000s)             1471.7
```

As indicated, all heads are below the safe elevations required. The solution consists of a single "superpipe" located just downstream of node 801. The reduction in the peak trunk flow is 123.9 cfs, resulting in a peak outflow from the storage unit of 16.50 cfs. From the assumed relationship between flow reduction and trunk in-line storage (cf., Appendix B), OPTSTOR calculates that 147,170. cu. ft. of storage is required. This is considerably higher than the foregoing case of smaller units at each node.

Since the superpipe's length is 0.5 x 571 = 286 ft. and its obvert is modelled to be identical to that of the original conduit (viz., 640.73 + 4.5 = 645.23 ft. at node 801), then the width of a rectangular superpipe would be determined as:

$$(147{,}170/286)/4.5 = 114.4 \text{ ft.}$$

The shape of the superpipe is noncircular, as losses are minimal; thus, noncircular shapes are valid and usually necessary.

ii) Local Off-line Storage: Table 5.5 a) shows the system flows, maximum water levels, calculated storages and cost for the OPTSTOR local off-line solution if all pipes are eligible for storage. Storage is concentrated where local inflows are highest. It may be physically impractical to provide storage at all locations, so storage is subsequently limited to the four most upstream nodes (i.e., 801, 803, 805, and 11). The results of this storage configuration appear in Table 5.5b).

As indicated, all heads are below the safe elevations required. The reductions in local inflows of 50.5, 28.2, 20.7 and 24.6 cfs translate to peak local inflows of 89.9, 61.0, 53.5, and 47.7 cfs for 801, 803, 805, and 11, respectively. From the assumed relationship between flow reduction and local off-line storage (cf., Appendix B), OPTSTOR calculates that 28,585, 15,977, 11,731, and 13,908 cu. ft. of storage are required at nodes 801, 803, 805, and 11, respectively.

TABLE 5.5 a) OPTSTOR LOCAL OFF-LINE RESULTS (ALL PIPES)

```
** PIPE RESULTS **

NUMBER    LABEL      FLOW       VELOCITY    HEAD LOSS
                     (CFS)       (FT/S)       (FT)

   1       801       99.81        6.28        2.26
   2       803      166.75        7.02       14.82
   3       805      224.63        9.45        2.05
   4        11      414.62       14.66        3.76
   5         9      437.22       15.46        5.92
   6         8      457.22       16.17        5.82
   7         7      476.14       16.84        7.55
   8         6      495.88       17.54       16.67
   9         5      501.15       17.72       15.15
  10         4      537.73       14.38        3.88
  11         3      558.43       14.93        7.35

** NODE RESULTS **

NUMBER    LABEL     HEAD      Q(IN/OUT)     REDUCTION    STORAGE      STORAGE
                                             IN FLOW     VOLUME        COST
                    (FT)       (CFS)         (CFS)      (CU. FT)      ($)

   1       801      645.2        0.00        40.57      20207.5     202075.
   2       803      643.0        0.00        22.28      10984.7     109847.
   3       805      628.1        0.00        16.33       8059.5      80595.
   4        11      626.1      136.00        18.34       8747.3      87473.
   5         9      622.3       22.60         0.00          0.0         0.
   6         8      616.4       20.00         0.00          0.0         0.
   7         7      610.6        0.00         6.53       2674.3      26743.
   8         6      603.0        0.00         5.91       2296.9      22969.
   9         5      586.4        0.00         2.32       1024.3      10243.
  10         4      571.2        0.00         9.01       3598.4      35984.
  11         3      567.3        0.00         4.02       1066.1      10661.

** SYSTEM RESULTS **

TOTAL STORAGE VOLUME (1000 CU. FT.)          58.7
TOTAL COST FOR STORAGE ($1000s)             586.6
```

TABLE 5.5 b) OPTSTOR LOCAL OFF-LINE RESULTS (4 PIPES)

```
** PIPE RESULTS **

NUMBER     LABEL       FLOW       VELOCITY    HEAD LOSS
                       (CFS)      (FT/S)      (FT)

   1        801         89.92       5.65        2.26
   2        803        150.94       6.35       16.85
   3        805        204.48       8.61        2.45
   4         11        388.26      13.73        3.30
   5          9        410.86      14.53        5.23
   6          8        430.86      15.24        5.17
   7          7        456.31      16.14        6.93
   8          6        481.96      17.05       16.67
   9          5        489.55      17.31       15.15
  10          4        535.14      14.31        3.84
  11          3        559.86      14.97        7.39

** NODE RESULTS **

NUMBER     LABEL      HEAD        Q(IN/OUT)   REDUCTION   STORAGE      STORAGE
                                               IN FLOW     VOLUME       COST
                      (FT)         (CFS)       (CFS)      (CU. FT)      ($)

   1        801       645.2         0.00        50.46     28585.3      285853.
   2        803       643.0         0.00        28.20     15976.8      159768.
   3        805       626.1         0.00        20.68     11730.5      117305.
   4         11       623.7       136.00        24.55     13908.3      139083.
   5          9       620.4        22.60         0.00         0.0           0.
   6          8       615.2        20.00         0.00         0.0           0.
   7          7       610.0         0.00         0.00         0.0           0.
   8          6       603.0         0.00         0.00         0.0           0.
   9          5       586.4         0.00         0.00         0.0           0.
  10          4       571.2         0.00         0.00         0.0           0.
  11          3       567.4         0.00         0.00         0.0           0.

** SYSTEM RESULTS **

TOTAL STORAGE VOLUME (1000 CU. FT.)           70.2
TOTAL COST FOR STORAGE ($1000s)              702.0
```

5.4 EXTRAN Simulation of OPTSTOR Solutions

Because of the assumptions made in OPTSTOR, the storage solutions proposed are conservative and satisfy the relief requirements of the sewer line. In an attempt to dynamically illustrate the Trunk In-line and Local Off-line solutions for the demonstration system, the hydrographs used as input to EXTRAN are modified to reflect the influence of the proposed relief measures.

i) Trunk In-line Storage: The trunk in-line storage solution is simulated by modifying the trunk flow hydrograph to include the effect of a "superpipe" at node 801. The modified hydrograph is introduced at a point 286 ft. (length of superpipe) downstream of the original node 801. Table 5.6 shows the system flows and maximum water levels for the EXTRAN simulation of this trunk in-line solution.

ii) Local Off-line Storage: The local off-line storage solution is simulated by "clipping" the appropriate local inflow hydrographs at the controlled outflow level given by OPTSTOR for nodes 801, 803, 805, and 11. Table 5.7 shows the system flows and maximum water levels for the EXTRAN simulation of the local off-line solution.

It should be noted that there are some differences between the results calculated by OPTSTOR and the results predicted by EXTRAN. The following comments are pertinent to simulation of both of the proposed relief measures by EXTRAN.

By using the integration step size suggested in the EXTRAN manual, it is not possible to achieve numerically stable simulations. After reducing the step, by increments, somewhat more stable simulations result with an integration step of 1 second, though the instability remains.

TABLE 5.6 SUMMARY OF EXTRAN SIMULATION OF TRUNK IN-LINE STORAGE AT 801

CONDUIT/ JUNCTION NUMBER	GROUND ELEVATION (FT)	MAXIMUM ALLOW. HEAD (FT)	MAXIMUM COMPUTED DEPTH (FT)	FEET OF SURCHARGE AT MAX. DEPTH	MAXIMUM COMPUTED ELEVATION (FT)	MAXIMUM FLOW (CFS)
801	655.70	645.73	1.05	0.00	640.45	16.4
803	652.50	644.47	2.46	0.00	639.96	98.3
804	641.70	633.70	2.67	0.00	628.57	119.1
805	636.20	628.15	16.10	10.10	636.20	252.9
12	640.00	632.00	23.70	19.20	640.00	146.7
11	639.60	631.57	24.80	17.28	639.60	380.8
9	637.90	629.90	26.30	20.02	637.90	405.2
8	635.30	627.30	28.30	21.70	635.30	434.8
7	628.00	619.98	24.50	18.07	628.00	444.4
601	609.90	603.20	4.22	0.00	602.12	544.7
6	609.90	603.20	25.00	19.00	609.90	557.3
501	592.80	586.50	12.40	6.40	592.80	574.6
5	592.80	586.50	19.40	13.40	589.20	576.7
4	579.20	571.23	6.59	0.00	569.19	539.2
3	576.60	568.63	6.84	0.00	566.44	513.5
2	575.30	567.30	5.62	0.00	564.02	498.2
1	574.90	566.90	5.89	0.00	561.09	494.8
100	575.30	567.30	5.82	0.00	559.72	

TABLE 5.7 SUMMARY OF EXTRAN SIMULATION OF LOCAL OFF-LINE STORAGE

CONDUIT/ JUNCTION NUMBER	GROUND ELEVATION (FT)	MAXIMUM ALLOW. HEAD (FT)	MAXIMUM COMPUTED DEPTH (FT)	FEET OF SURCHARGE AT MAX. DEPTH	MAXIMUM COMPUTED ELEVATION (FT)	MAXIMUM FLOW (CFS)
801	655.70	647.73	2.69	0.00	643.39	90.2
803	652.50	644.47	3.23	0.00	640.73	164.6
804	641.70	633.70	4.28	0.00	630.18	221.9
805	636.20	628.15	16.10	10.10	636.20	282.7
12	640.00	632.00	23.70	19.20	640.00	139.4
11	639.60	631.57	24.80	17.28	639.60	398.5
9	637.90	629.90	26.30	20.02	637.90	423.8
8	635.30	627.30	28.30	21.70	635.30	444.9
7	628.00	619.98	24.50	18.07	628.00	469.4
601	609.90	603.20	4.48	0.00	602.38	557.4
6	609.90	603.20	25.00	19.00	609.90	578.4
501	592.80	586.50	3.43	0.00	583.83	582.9
5	592.80	586.50	23.00	17.00	592.80	552.2
4	579.20	571.23	16.60	9.60	579.20	558.3
3	576.60	568.63	7.61	0.63	567.21	567.8
2	575.30	567.30	5.97	0.00	564.37	522.8
1	574.90	566.90	6.33	0.00	561.53	518.4
100	575.30	567.30	5.92	0.00	559.82	

Despite the fact that none of the heads exceed the maximum allowables at any of the one-minute print intervals, the summary tables predict short periods of flooding to ground level at a few locations. In light of the increase in head necessary to cause flooding and the short interval in which flooding is predicted (less than 1 minute), it is felt that the predictions are erroneous.

Plots of the heads at critical nodes indicate numerical instability. However, except for "spikes" where the heads exceed the maximum allowable head, the plots are smooth with peaks well below the maximums. This also seems to indicate that the predicted flooding results from the still-present numerical instability and is not a physical reality.

Our results reinforce the need to improve EXTRAN's calculation module, especially when a free surface vanishes, or to substitute a new dynamic combined open-channel/closed-conduit program.

APPENDIX A

RELATIONSHIP BETWEEN OPTSTOR AND DYNAMIC MODELS

A.1 GENERAL DESIGN METHOD

As noted in Sections 1 and 5, OPTSTOR is used, as part of an overall design method in combination with an urban runoff model and a dynamic flow routing model of a sewer system.

The development of storm sewer relief measures, based on storage, proceeds in the following manner:

i) An urban runoff model of the subject area is developed and runoff hydrographs are simulated for all sub-catchments contributing local inflows to nodes (manholes) in the storm sewer system.

ii) A dynamic routing model of the storm sewer system is established and the heads and flows in the existing system are simulated. If the peak water levels are excessive, then one proceeds to iii).

iii) The storm sewer system is conceptually decomposed into a set of individual sewer lines to be modelled independently using OPTSTOR.

iv) Each sewer line to be considered is isolated and peak local inflows, at each node (manhole) in the line, are abstracted from the urban runoff model. Trunk inflows, at nodes where connections with other sewer lines exist, are obtained from the dynamic flow routing model as is the water level at the downstream end of each isolated line.

v) OPTSTOR input for each sewer line is prepared from the physical characteristics of the individual line and the information obtained from the runoff and dynamic simulations.

vi) Each storm sewer line is examined using OPTSTOR. If necessary, steps iii) to v) are repeated to refine the solution.

vii) A second simulation of the dynamic behaviour of the system may be desirable to illustrate the effects of the proposed relief measures. The storage is represented by means of modified hydrographs.

During OPTSTOR's development, it was used in conjunction with the SWMM/EXTRAN model only. It could, however, be used in combination with other dynamic models such as the proprietary Dorsch model.

viii) Certain relief measures can be physically designed and included in the dynamic model. This requires both a dynamic model that can accurately simulate the behaviour of the relief measures and a trial-and-error approach on the part of the designer. In some instances, however, the final detailed design may have to be performed using a separate independent model or done manually.

A.2 USING OPTSTOR IN CONJUNCTION WITH SWMM/EXTRAN

The general design method described above will be discussed in greater detail, with reference to the SWMM/EXTRAN model, in the following sections.

A.2.1 The SWMM/EXTRAN Model

The SWMM RUNOFF Block is used to model surface runoff from each subcatchment. The result is a local inflow hydrograph at each node (manhole) of the storm sewer system. Generally, a design storm such as the Chicago storm is used as input to the model.

The EXTRAN Block is used next to simulate the hydraulics of the sewer system. Setting up EXTRAN consists of a description of the "connectivity" of the pipe system, the length, slope and roughness of each pipe, inverts of manholes, descriptions of special devices such as weirs or orifices, etc. The model calculates flows and water levels in the system at discrete time steps through the duration of the input hydrographs.

The application of the SWMM/EXTRAN model to the demonstration system (cf., Section 5) followed the standard procedure used in the analysis of any sewer system.

A.2.2 Preparation for OPTSTOR Analysis

The initial EXTRAN simulation results are examined to determine which sewer lines in the system are subject to flooding or excessive surcharging. Surcharging, above safe levels, indicates lines that will benefit from analysis using OPTSTOR.

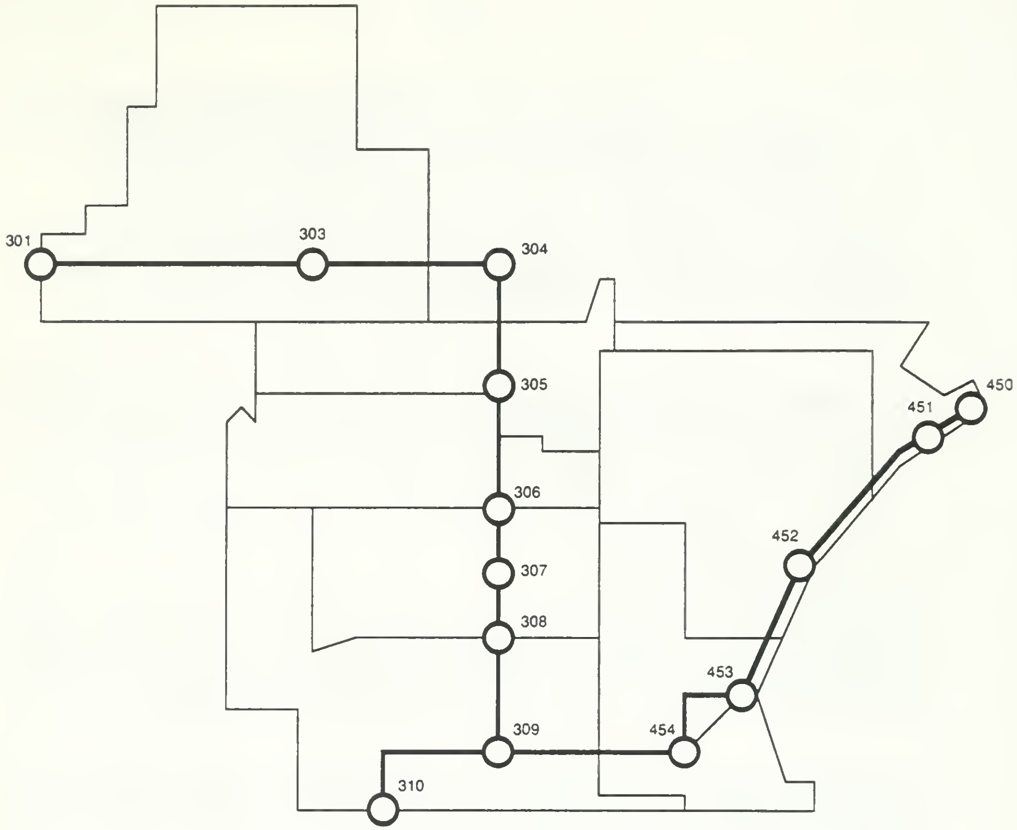
Since OPTSTOR can simulate only one sewer line at a time, the pipe system must be conceptually decomposed into a number of separate lines. In most cases, this is straightforward since the system consists of a number of well-defined distinct branches. Figure A-1 shows an example of a system and one possible decomposition. In other cases, the system may have inter- connections between branches or loops which make the task more difficult.

With each line of the system separated for the purposes of analysis, the following information must be extracted from the SWMM/EXTRAN results.

a) The peak local inflow at each node in the sewer line is obtained from the SWMM Runoff Block.

b) The impervious area contributing at each node can be calculated by summing the drainage area at each point weighted with its imperviousness as presented in the SWMM Runoff Block output.

c) The peak trunk inflow or outflow at each node, from other "separate" interconnecting lines, is obtained from the EXTRAN output.



Schematic of Complete System

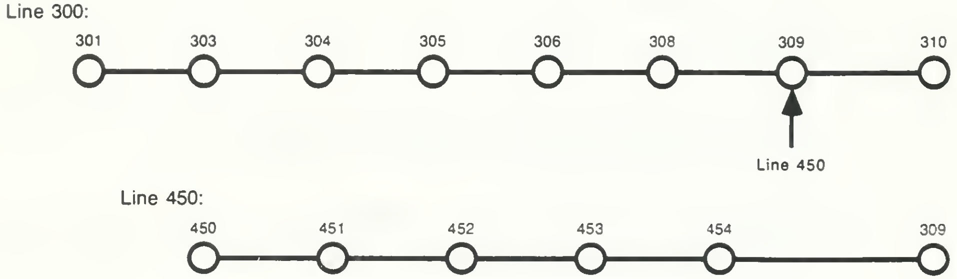


Figure A – 1

Example of Network Decomposition

d) The peak water level at the downstream end of the sewer line is obtained from the EXTRAN output. This may be the same value for several lines if they branch from a common point.

All other OPTSTOR data can be obtained directly from the physical description of the system. The SWMM/EXTRAN model input is a convenient source of the required data.

It is worth noting that not every pipe and manhole in the original system must be included in the OPTSTOR analysis. If pipe sizes are the same in successive links, if no inflow occurs at a node or there is no possibility of storage at a node, then some "lumping" of the system may be feasible.

A.2.3 OPTSTOR Analysis

Details of the use of the OPTSTOR program are given in Sections 2, 3 and 4 of this manual. Those sections cover the method of specifying the input data, how to run the program and what type of output to expect .

In this section, a brief discussion of the typical steps involved in an OPTSTOR analysis is presented. In general this may consist of the following:

i) Set up separate files containing the data describing each isolated sewer line.

ii) Decide on the order in which the lines will be analysed. (This is probably arbitrary since each analysis is independent.)

iii) Select a type of storage to be considered initially in the first line to be examined. This can be one of the four types described in Section 1.

iv) Execute an OPTSTOR program run.

v) Refine the OPTSTOR solution. This may consist of varying the safe maximum heads specified, varying the "superpipe ratio", eliminating some nodes as possible storage locations or varying the diversions from the line in question. It may also include modifying the input data to specify enlargement of drastically undersized pipes. Such constricted sections can generally be spotted by examining the OPTSTOR output showing the head loss in each pipe link.

vi) Repeat steps iv) and v) for other types of storage. This process can be continued until the solution is satisfactory.

vii) Iterate steps iii) to vi) for each line to be examined.

At the end of the OPTSTOR analysis, a set of storages (and, optionally, pipe enlargements) that provide relief of the storm sewer system, considered as independent lines, will have been derived. Because of the conservative assumptions embedded in OPTSTOR, the cumulative solution will satisfy the relief requirements of the system as a whole.

However, because the lines are not truly independent, it may be desirable to make further iterations through the EXTRAN - OPTSTOR analysis cycle to account for the relief measures. In order to do this, it is necessary to simulate the proposed relief measures with EXTRAN.

It should not, however, be necessary to make more than one iteration through the OPTSTOR analysis.

A.2.4 Simulation of Relief Measures Using SWMM/EXTRAN

This section provides suggestions on how the effects of relief measures, proposed by an OPTSTOR analysis, can be simulated by means of EXTRAN.

a) Trunk in-line storage is achieved by routing the trunk hydrograph through a storage facility with a specified stage-storage-discharge relationship. The effect of storage is to attenuate and delay the peak flow in the trunk hydrograph. Trunk in-line storage can be simulated by modifying the trunk hydrograph to reflect this effect.

   To get access to the trunk hydrograph, the EXTRAN model must be "broken" at the locations where storage is desired. The trunk hydrograph can then be modifified to reflect the delayed, reduced peak flow calculated by OPTSTOR and provided as input to the downstream portion of the model.

b) Trunk off-line storage is achieved by a diversion of trunk flow from the sewer line above a specified maximum flow. The effect of storage is to "clip" the trunk flow hydrograph creating a sustained, reduced peak on the hydrograph. Trunk off-line storage can be simulated by modifying the trunk hydrograph to reflect this effect.

   To get access to the trunk hydrograph, the EXTRAN model must be "broken" at the locations where storage is desired. The top of the trunk hydrograph can then be "clipped" at the peak level calculated by OPTSTOR and provided as input to the downstream portion of the model.

c) Local in-line storage is achieved by routing the local inflow hydrograph through a storage facility with a specified stage-storage-discharge relationship. The effect of storage is to attenuate and delay the peak flow in the local inflow hydrograph. Local in-line storage can be simulated by modifying the local inflow hydrograph to reflect this effect.

   The local inflow hydrograph can be modified to reflect the delayed, reduced peak flow calculated by OPTSTOR and provided as input to the model.

d) Local off-line storage is achieved by a diversion of local inflow, before it enters the system, above a specified maximum inflow. The effect of storage is to "clip" the local inflow hydrograph creating a sustained, reduced peak on the inflow hydrograph. Local off-line storage can be simulated by modifying the local hydrograph to reflect this effect.

The top of the local inflow hydrograph can be "clipped" at the peak level calculated by OPTSTOR and provided as input to the model.

These modified hydrographs can be provided as input to EXTRAN in the form of "card hydrographs".

APPENDIX B

DEVELOPMENT OF STORAGE/IMPERVIOUS AREA VERSUS FLOW REDUCTION CURVES

B.1 OVERVIEW

OPTSTOR is designed to estimate the optimum amount of storage required in an overloaded sewer system to reduce flows to a point where resulting water levels are less than critical elevations.

A fundamental assumption in the OPTSTOR methodology is that a consistent relationship exists between the relative reduction in peak flow and the storage volume required to achieve that reduction. This is true if the shape of a runoff hydrograph is relatively consistent from one node in the system to another.

This assumption is well met, within the framework of SWMM/EXTRAN modelling, if a consistent design storm (i.e., a "Chicago" type storm) is used. If an alternative type of storm is to be used, different curves must be developed from SWMM/EXTRAN simulations.

A further assumption implicit to the OPTSTOR methodology is that the shape of a hydrograph, after routing through storage, is also consistent from node to node, for a given type of storage.

For in-line storage, an assumed linear increase in flow from the start of the steeply inclined section of the rising limb of the unrouted hydrograph, to the point on the recession limb which equals the required design outflow provides a consistent shape to the outflow hydrograph (see Figure B-1 a) for an illustration of this concept).

For off-line storage, in which hydrographs are simply 'clipped' at a level equal to the required design flow, the shape of the outflow hydrograph is consistent (see Figure B-1 b)).

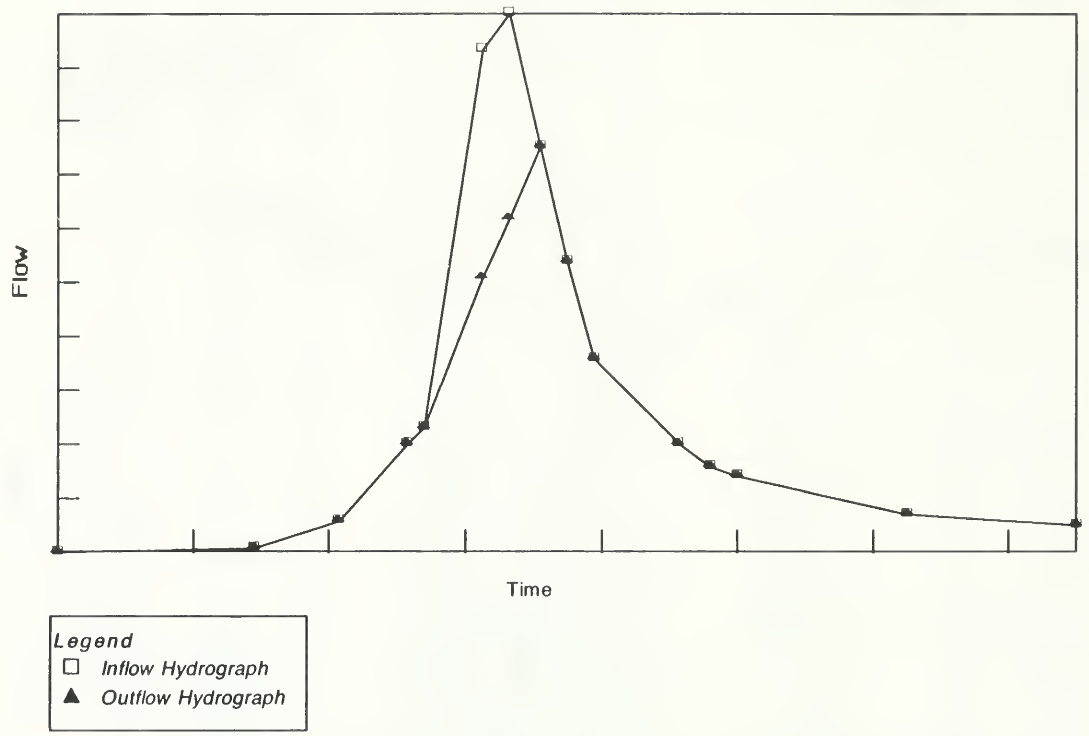


Figure B – 1 a)

In – line Storage: Assumed Shape of Outflow Hydrograph

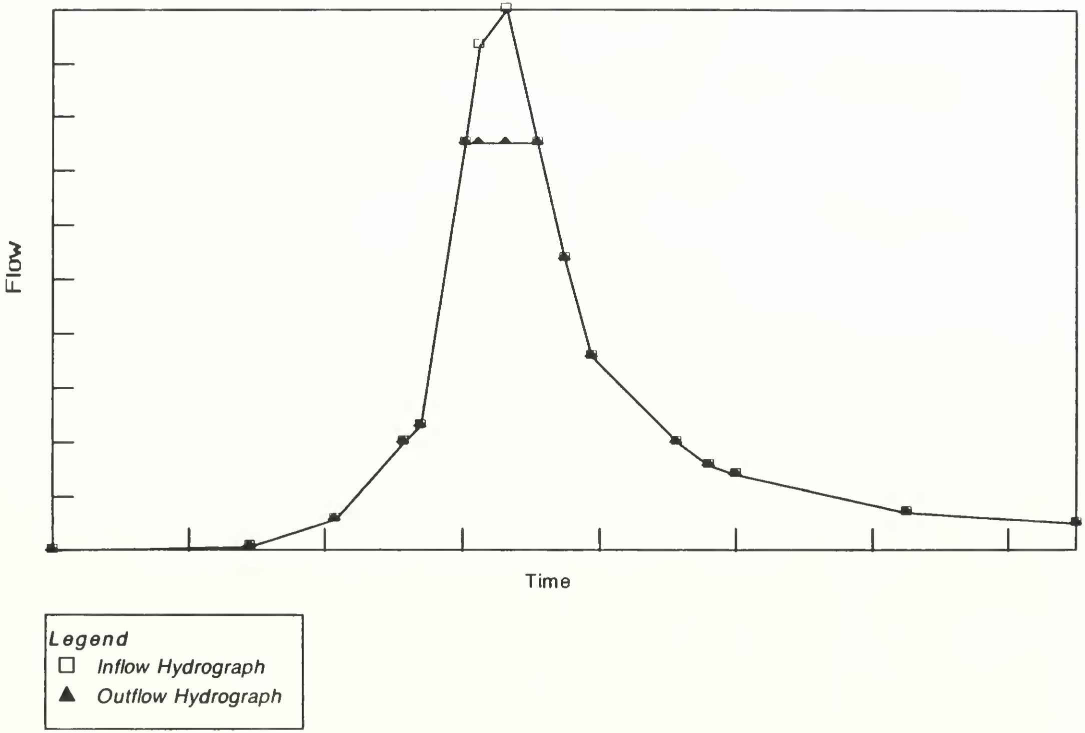


Figure B – 1 b)

Off – line Storage: Assumed Shape of Outflow Hydrograph

Given the above assumptions, the volume of storage required to achieve a given degree of flow reduction can be calculated by finding the difference in area between unrouted and routed hydrographs before they cross on the recession limb. By assuming various degrees of flow reduction, a curve can be obtained for each point in a particular system. Analysing a large number of points in a system provides many curves which can then be generalized by regression analysis.

The 'normalizing' parameter found to be most useful during regression analysis was the impervious area of each sub-catchment. Hence, equations based on storage volume per impervious acre were developed.

B.2 RESULTS

The above approach was applied to the Edmonton system for which the OPTSTOR methodology was originally developed and the demonstration system used in this study as described in Section 5. In both cases, the hydrographs from the SWMM/EXTRAN model at each node in the system were analysed. Curves were developed for the four different types of storage (i.e., trunk in-line, trunk off-line, local in-line, local off-line) used in OPTSTOR. For both systems, the curves were very similar. The regression equations describing these curves were of the type:

$$\text{VOL / IMP.ACRE} = \text{CONST} * (\text{RELATIVE FLOW REDUCTION})^{\text{EXP}}$$

where CONST is a constant factor and EXP is an exponent suitable to the type of storage being considered. The curves are displayed in Figure B-2.

For the four types used in OPTSTOR, the foregoing parameters have the following values (based on the two abovementioned systems):

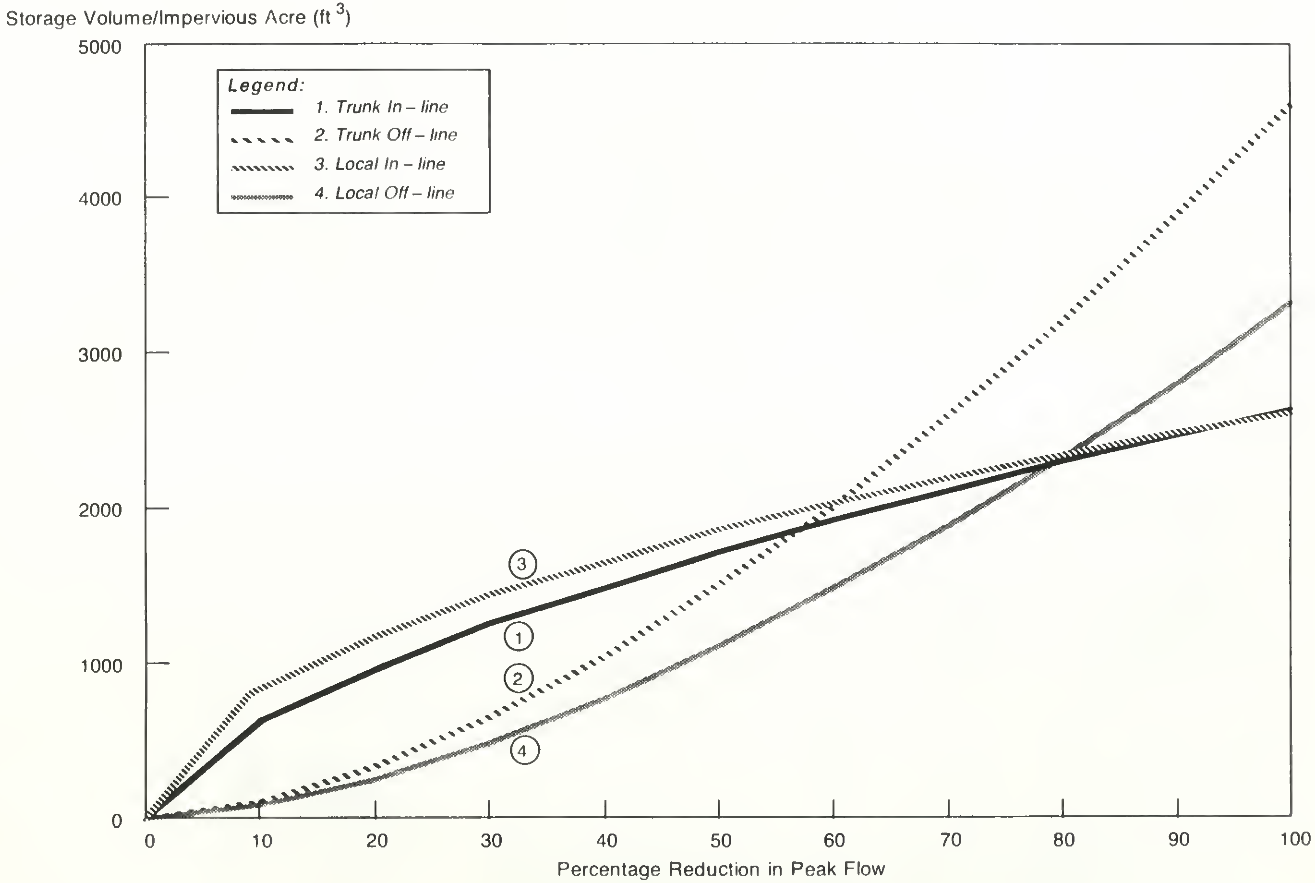


Figure B – 2

Storage Volume per Impervious Acre to Achieve Specified Percentage Reductions in 5 – Year Peak Flow

Trunk In-line: CONST = 2630. EXP = 0.62
Trunk Off-line: CONST = 4600. EXP = 1.62
Local In-line: CONST = 2620. EXP = 0.50
Local Off-line: CONST = 3320. EXP = 1.59

The storage volume equations differ for two reasons:

a) The trunk flow hydrograph is broader than the local inflow hydrograph. This changes the relationship between storage volume and resultant flow reduction. For the off-line case, the volume of trunk storage always exceeds that of local storage; the reverse is valid for in-line storage.

b) The hydrograph resulting from in-line storage requires much more storage than the 'clipped' hydrograph resulting from off-line storage for small to moderate percentage reductions in peak flows. See Figure B-1 for an illustration of this difference. For large percentage reductions (above 60% for trunk and 80% for local), the reverse is true.

APPENDIX C

COMPLEX METHOD FOR NONLINEAR CONSTRAINED OPTIMIZATION

C.1 OVERVIEW

The Complex Method, developed by Box (1965), is a method for nonlinear constrained optimization based on the Simplex Method for unconstrained optimization.

Both the explicit and implicit constraints are inequalities of the form:

$$\begin{aligned} \text{expllower}(i) &\le \text{explvar}(i) \le \text{explupper}(i) \\ \text{impllower}(i) &\le \text{implvar}(i) \le \text{implupper}(i) \\ i &= 1, 2, \ldots, n, \end{aligned}$$

where the implicit dependent variables, implvar(i), are functions of the explicit independent variables, explvar(i). The upper and lower limits for each are either constants or also functions of the independent variables.

Box's original formulation of the method consists of two distinct components:

i) develop a set of initial solutions which span the constrained solution space and evaluate the objective function for each,

ii) use these initial solutions to search for other acceptable solutions with more favourable objective function values.

C.2 OPTSTOR APPLICATION

For the OPTSTOR application, the constrained independent variables are the ratios of stored flow to total storable flow at the nodes. The constrained dependent variables are the heads at the nodes.

The objective function, for the OPTSTOR application, is the sum of the individual storage volume costs at each node. Both the objective function and the implicit constraints are nonlinear.

The optimization performed is a minimization of this sum, which is the total storage cost.

C.3 DEVELOPING THE INITIAL SOLUTION COMPLEX

The first component of the Complex Method is the "random" development of n+1 solutions in the constrained solution space of the n independent variables. In this context, the term "random" is meant to imply that the solutions are sufficiently different from one another, in terms of the independent variable, that they represent diverse points in the constrained solution space.

Box determined that n+1 solutions are required in order to "prevent the configuration from prematurely collapsing into a sub-space".

Initially, trial solutions representing the extreme of storage at a single node are developed. The remaining trial solutions are developed, for the required complex of n+1 solutions, by randomizing the ratio R of the stored flow to the total storable flow at a node.

Each trial solution is checked against the explicit and implicit constraints to determine if they are satisfied. If this is the case, a trial solution will become one of the solution complex "points"; otherwise, the trial solution is discarded.

Developing and checking of trial solutions continues until the required number of feasible solutions is attained.

C.4 COMPLEX OPTIMIZATION

Optimization of the solution complex proceeds by systematically modifying the least favourable existing complex point (i.e., the solution with the greatest total storage cost) in order to define a new point with a more favourable objective function value (i.e., a solution with a lower total storage cost). The complex point representing the most expensive solution is replaced by its "over-reflection" about the centroid of the points representing lesser cost solutions to create this trial point.

The term "over-reflection" means that the trial point is produced on a line connecting the rejected point and the centroid, opposite the rejected point. Based on empirical findings, Box has recommended that the trial point be a distance 1.3 times as far from the centroid as the rejected point. The reason for the over-reflection is explained in the following excerpt from Box's paper.

"It is considered that as the initial configuration is generated so as to roughly span the feasible region, the first few iterations will be even more likely to span the whole of this region. Consequently it seems reasonable to suppose that if several local minima exist, and one of these corresponds to a very much smaller function value than the rest, then this best local minimum (the global minimum) will be found."

Problems can arise if either the aforementioned centroid or the new point is infeasible or too costly. If the centroid is the problem, then a "reduced" centroid is obtained by successively omitting the most costly complex point until a sub-complex is obtained whose centroid is "good" (i.e., feasible and cheaper than the second most expensive solution). It is possible that the sub-complex could consist of only one point, the least costly solution. On the other hand, the new point obtained by over-reflecting about the (reduced) centroid can also not be "good". Should this occur, it is modified by bisecting the distance between itself and the reduced centroid. The latter process is repeated until the modified point is good or is so close to the reduced centroid that it is set equal to this point.